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ABSTRACT

Anomalous behavior of ionospheric total electron content (TEC) prior to earthquake has been observed in many studies. Evidence of such seismo-ionospheric coupling effects suggests that it is plausible to rely on TEC signatures for early earthquake warning. However, the detection of pre-earthquake TEC anomalies (PETA) has not been adopted in practice due to two pertinent issues. Firstly, the effects of space weather activity can affect TEC levels and cause anomalous behavior in the TEC. Usually arbitrary thresholds are set for space weather indices to eliminate TEC anomaly due to space weather effects. Secondly, the choice regarding moving time-window length used to characterise background variation of TEC within the statistical envelope approach has an effect on detection of PETA. While the rule-of-thumb in selecting the moving window length is to have a time window capable of capturing background variability and short-term fluctuations, the length of the time window used in the literature varies with little justification. In this study, a critical examination is conducted on the statistical envelope approach and in particular, to eliminate the effect of space weather activity without the use of arbitrary space indices to detect PETA. A two-part PETA identification procedure is proposed, consisting of wavelet analyses isolating non-earthquake TEC contributions, followed by the statistical envelope method using a moving window length standardized based on observed periodicities and statistical implications is suggested. The approach is tested on a database of 30 large earthquakes ($M \geq 7.0$). The proposed procedure shows that PETA can be detected prior to earthquakes at higher confidence levels without the need to separately check for space weather activity. More importantly, the procedure was able to detect PETA for studies where it was previously reported that PETA could not be detected or detected convincingly.

Keywords: Earthquake; Pre-cursor; Ionosphere; Total electron content; Space weather; Statistical envelope methods

1 Introduction

There has always been a keen interest in the search for a reliable precursor of large magnitude earthquakes. The list of electromagnetic geophysical phenomena that has been investigated as a possible earthquake precursor includes observations in the very low and ultra-low frequency (VLF, ULF) spectrum, infra-red and thermal emissions, particle precipitation, cloud atmospheric dynamics, seismic quiescence, Benioff strain rates, well levels, ground water temperatures and even the relatively contentious animal behavioral anomalies (Albarello et al. 1991; Aleksandrin et al. 2003; Choudhury et al. 2006; Guangmeng and Jie 2013; Habermann 1988; Hayakawa et al. 2007; Hayakawa et al. 2010; Orihara et al. 2014; Ouzounov and Freund 2004; Papazachos and Papazachos 2001; Yosef 1997). In particular, the link between seismic preparation and its perturbations of the ionosphere has been observed for over 50 years with the early stages of its development aptly summarized by Pulinet and Boyarchuk (2004). Seismo-ionospheric concepts (e.g. lithosphere-atmosphere-

ionosphere coupling and positive-holes) have been proposed in the literature in order to elucidate the causes of seismic preparatory influences on the ionosphere (Freund 2011; Freund et al. 2009; Popov et al. 1989; Pulinets and Ouzounov 2011). A summary of publications (till year 2015) in the Web of ScienceTM database illustrates that the ionospheric parameter – total electron content (TEC) predominates the various types of precursors, followed by ground chemistry-related parameters such as radon emanations (Figure 1). Even though numerous studies exist in the literature revealing the presence of ionospheric perturbations due to earthquakes, this phenomenon has yet to be accepted by the scientific community and to an even greater extent, those within the seismological discipline (e.g. Geller et al. 1997; Hough 2016 and references therein). The skepticism is not helped by studies which show that ionospheric perturbations before an earthquake are only present in 50 to 70% of the database of past earthquakes investigated (e.g. Guo et al. (2016), Liu and Xu (2017) and Yan et al. (2014)).

There has been an intensification of efforts within the past two decades to examine the correspondence between various ionospheric and earthquake parameters (Afraimovich et al. 2004; Klimenko et al. 2011; Pulinets and Boyarchuk 2004; Van Dam et al. 2009). The advent of space technologies (e.g. greater availability of low-earth orbiting satellites) and increased remote-sensing instrumentations (e.g. global positioning system (GPS) stations) have provided better resources for ionospheric observations. With constant measurements of the ionosphere, TEC data derived from GPS stations provide regular and timely information about ionospheric fluctuations.

Relying on GPS signal delays through the ionosphere (Eq. 1), many researchers have reported the occurrences of pre-earthquake TEC anomalies (PETA) preceding earthquakes of various magnitudes, such as the 2008 China (Wenchuan), 2010 California (United States) , 2011 Japan (Tohoku), 2012 Mexico, 2013 Greece (Crete) as well as the recent 2015 Nepal and Chile events (e.g., Aggarwal 2015; Akhoondzadeh 2012; Cahyadi and Heki 2013; Chen et al. 2004; Choi et al. 2012; Contadakis et al. 2015; Guo et al. 2015; Hsiao et al. 2010; Jhuang et al. 2010; Leyva-Contreras et al. 2005; Liu et al. 2009; Liu et al. 2000; Oikonomou et al. 2016; Pulinets et al. 2006; Sánchez-Dulcet et al. 2015; Ulukavak and Yalcinkaya 2016; Yiyen et al. 2009; Zakharenkova et al. 2007).

$$TEC = \frac{f_1^2 f_2^2 (P_1 - P_2 - b_r - b_s)}{40.3(f_2^2 - f_1^2)} \quad (1)$$

where f_1, f_2 denote GPS dual-frequencies, P_1, P_2 denote pseudo-range for each frequency, b_r, b_s denote differential code bias of receiver and satellite respectively.

In order to understand the current impediments of PETA, consideration is given to two major factors influencing the PETA detection process and outcome. Firstly, among the various anomaly detection approaches, the statistical envelope method (e.g. moving-mean and median-based) is the most popular and have been successfully utilized by various researchers due to its convenience and seemingly intuitive interpretation (Astafyeva and Heki 2011; Chauhan et al. 2009; Dogan et al. 2011; He et al. 2012; Jing et al. 2011; Liu et al. 2010; Liu et al. 2000; Nenovski et al. 2015; Oikonomou et al. 2016; Pulinets et al. 2004; Pundhir et al. 2014). The formulations for mean (i.e. Eq. 2) and median-based approaches are somewhat similar, where abnormal TEC levels are identified on the basis of a moving window (i.e. N), confidence level (i.e. z) and standard deviation (i.e. σ). Ideally, the value of N should be as large as possible to provide better statistical characterization (e.g. at seasonal

timescales) and yet short enough to capture local variability (Dautermann et al. 2007; Karatay et al. 2010). However, such a definition is counterintuitive due to varying levels of seismic activity and ionospheric variations (Araujo - Pradere et al. 2005). Consequently, without a standardized criterion or statistical implication, N has previously been assumed from between four days to two months without adequate justification (Aggarwal 2015; Astafyeva and Heki 2011; Chauhan et al. 2009; Chen et al. 2004; Fuying et al. 2011; Guo et al. 2015; Guo et al. 2016; Hasbi et al. 2011; He et al. 2014; Jhuang et al. 2010; Jing et al. 2011; Karatay et al. 2010; Ke et al. 2016; Nenovski et al. 2015; Oikonomou et al. 2016; Thomas et al. 2017; Ulukavak and Yalcinkaya 2016; Xu et al. 2013; Yiyen et al. 2009).

$$PETA: |TEC_{CURRENT}| > TEC_{MEAN,N} + z\sigma \quad (2)$$

From the observed dissimilarities in N , Thomas et al. (2017) briefly questioned the validity of a prescribed N (i.e. 15 days in their study) for PETA detection and examined an even longer window (i.e. two months). However, a longer window may imply a more relaxed criterion for anomaly detection (Lijffijt et al. 2012). Conversely, transient, short-term variations could result in more stringent detection bounds (assuming confidence levels remain the same). Nonetheless, N is dependent on the variability of the TEC data itself and a more judicious way of selecting N is necessary in order to avoid type I and II errors (i.e. false positives and false negatives).

Secondly, it is well known that variations in ionospheric TEC levels arise from the complex and dynamic electromagnetic geophysical interactions such as space weather activity, anthropogenic effects (e.g. missile launches) and meteorological events (e.g. stratospheric sudden warming) (Kakinami et al. 2013; Masci 2012). Among these factors, it has been shown that ionospheric conditions are highly modulated by space weather effects (e.g. solar and geomagnetic activity). For example, Dautermann et al. (2007) found that TEC is dominated by the cyclical nature of daily solar activity and lunar tides, giving rise to diurnal and semi-diurnal periodicities. Masci et al. (2017) similarly reported the presence of such cycles in what was construed as TEC anomalies in Nenovski et al. (2015). Moreover, Afraimovich et al. (2008) revealed that the global electron content follows a strong 27-day cycle (due to ultraviolet radiation and geomagnetic activity) accounting for large changes to the amplitudes of TEC (i.e. up to 20-30% deviations) (Afraimovich and Astafyeva 2008; Astafyeva et al. 2008). Masci (2013) further scrutinized TEC (i.e. 1999 Hector Mine earthquake) with concurrent geomagnetic indices (i.e. K_p and Dst) and discovered good correlation between them, proving that the TEC fluctuations could be explained by normal solar-terrestrial interactions. Likewise, Rhoades et al. (2015) analyzed ionospheric TEC over New Zealand (i.e. 2011 Christchurch earthquake) and discovered that the detected TEC anomaly coincides with a solar coronal mass ejection (CME) event which resulted in post-geomagnetic changes.

In light of these studies, it is challenging to prove a causal link between TEC anomalies and earthquake occurrence as space weather-induced changes are expected to be much stronger than any possible seismic-related contribution. Relying on one statistical envelope test to pick up seismo-ionospheric signatures (if any) is problematic since solar-induced effects (whether periodic oscillations or flare events) could potentially overwhelm these signals. For instance, the conclusions by various authors (i.e. Le et al. 2011; Nenovski et al. 2015; Pulinets and Davidenko 2014; Pulinets et al. 2007; Su et al. 2013) supporting the presence of PETA have led to several works (Afraimovich and Astafyeva 2008; Masci 2013; Masci and Thomas 2015; Thomas et al. 2017; Thomas et al. 2012) denouncing such links as due to

space weather influences. To be certain that a TEC anomaly is only caused by earthquake, various space weather indices, such as solar flux index (F10.7), disturbance storm time (Dst) and Kp-index (Devi et al. 2014; Saba et al. 1997) during the TEC anomaly occurrence is examined to check that these space weather indices fall below a certain threshold (i.e. non-influential). The ranges of values for each of these indices are summarised in Table 1. Analogous with the issue of N discussed earlier, these thresholds are highly subjective and unintuitive. For instance, Masci (2012) questioned the findings of Kon et al. (2011) on the basis of misinterpretations in the normal levels of geomagnetic activity.

Therefore in this study, non-earthquake related signals from raw measurements of TEC are identified and eliminated using the wavelet transform method based on the periodicities of space weather activity. Subsequently, the statistical envelope method is applied on the resulting analytical TEC signal by selecting an appropriate N. The detection of TEC anomaly is then validated using a database of recent earthquake events with inspection of earthquake cases studied previously.

2 Data Sets and Methods

A database consisting of 30 recent large earthquakes (i.e. $M \geq 7.0$) that occurred between 2011 and 2016 was assembled from the Earthquake Hazards Program database published by the United States Geological Survey (USGS). These include significant events such as the 2011 Japan (Tohoku) as well as the 2015 Nepal and Chile earthquakes. Epicenter coordinates (i.e. latitude and longitude) were utilised as the reference locations for these events. A summary of earthquake occurrence dates, epicenter coordinates, focal depth and magnitude is listed in Table 2.

There are various sources of TEC measurements available, such as space-borne platforms (e.g. SWARM and COSMIC satellites) as well as ground-based GPS receivers (e.g. stations in the International GNSS Service (IGS) network). Since ground receivers are capable of probing a larger extent of the ionosphere, TEC data is obtained from the Centre for Orbit Determination of Europe (CODE) in the form of global ionospheric maps (GIMs). Furthermore, GIM-TEC has been widely regarded as an accuracy reference (Mannucci et al. 1998; Yue et al. 2012). GPS signals from IGS stations are used to estimate TEC values using the spherical harmonic (SH) expansion technique up to degree of order 15 (Eq. 3), with GIM-TEC outputs provided at hourly intervals covering $\pm 87.5^\circ$ latitude and $\pm 180^\circ$ longitude at discretized spatial resolutions of 2.5° by 5° .

$$VTEC(\beta, s) = \sum_{n=0}^{n_{\max}} \sum_{m=0}^n \tilde{P}_{nm}(\sin \beta) (a_{nm} \cos ms + b_{nm} \sin ms) \quad (3)$$

where β is the latitude of ionospheric pierce point (IPP) in solar-geomagnetic reference frame; s is the sun-fixed longitude of IPP, a_{nm} and b_{nm} are SH coefficients of ionospheric model, and $\tilde{P}_{nm} = \Lambda(n, m) P_{nm}$ is the normalized associated Legendre polynomials, where $\Lambda(n, m)$ is the normalization function and P_{nm} is the un-normalized Legendre polynomials.

Since the nodal points for GIM-TEC do not necessarily coincide with epicenter locations, TEC values were obtained via interpolation using a cubic spline function based on neighbouring values. For the purposes of investigating space weather phenomena, common indices (e.g. F10.7, Kp and Dst) were not used in order to circumvent the need for arbitrary thresholds. Instead, the presence of such effects were identified purely based on the wavelet spectrum which provides frequency, time and amplitude information. The presence of solar flares was characterized using solar x-ray flux measurements in the short (0.05 – 0.4 nm) and

long channels (0.1 – 0.8 nm) from the GOES-15 geostationary satellite (Bornmann et al. 1996).

Analysis of the TEC signal constituents and intrinsic variations assume a two part process comprising of frequency and time domain examinations. As fluctuations in the ionosphere are a result of the dynamic solar-terrestrial interactions, TEC is understandably controlled by solar electromagnetic radiation. In essence, the solar radiation and associated effects (i.e. geomagnetism) serve as a noisy background to the TEC signal, which confounds processing and interpretation. It has been shown that such background solar contributions possess rapid and nonlinear variations (He et al. 2012). In order to remove space weather influences along with short-term (e.g. semi-diurnal and diurnal) oscillations, the wavelet transform method, which is highly effective for nonstationary signals, is used to analyse raw TEC data in the frequency spectrum (Mallat 2008). Compared to Fourier transforms, wavelets have finite energy and thus provide better time-frequency localizations. Using the continuous wavelet transform (CWT), the TEC signal is analyzed in a multi-resolution approach (i.e. different frequencies) through scaling and translations of the mother wavelet (ψ). Scaling and translations of the wavelets relate to frequencies and time information, respectively. The mother wavelet serves as a window analogous to the short-time Fourier transform, but has a varying size dependent on the scaling parameter. Among the various mother wavelets, the Morlet (or sometimes, Gabor) wavelet was selected because of its simplicity and convenience when studying wave-like events, such as those within the atmosphere-ionosphere systems (Liner 2010; Torrence and Compo 1998). Additionally, its non-orthogonality implies that both low and high frequency TEC components can be adequately represented. The values (i.e. coefficients) of CWT implies correlation between the continuous TEC-time signal and ψ .

Formulations for CWT (W_ψ^y) and Morlet analyzing wavelet are illustrated in Eqs. (4) and ((5), respectively. Thus, the frequency and temporal variability of ionospheric TEC can be simultaneously assessed over the length of the signal.

$$W_\psi^y(a, b) = \frac{1}{\sqrt{|b|}} \int_{-\infty}^{\infty} y(t) \cdot \Psi^* \left(\frac{t-a}{b} \right) dt \quad (4)$$

$$\Psi(t) = e^{-\frac{t^2}{2\sigma^2}} e^{i\omega_o t} \quad (5)$$

where a , b refer to the scaling and translational parameters respectively; $y(t)$ refers to the raw and unfiltered TEC signal; $\Psi^*(t)$ refers to the complex (i) conjugate of the analyzing wavelet ($\Psi(t)$); t refers to time; ω_o refers to wavelet's frequency; σ is a measure of the wavelet's support.

Solar and geomagnetic-induced periodicities were systematically identified and removed from the raw TEC data by observing the wavelet spectrum and applying detrending and suitable filters (e.g. bandstop, or bandpass) at frequencies corresponding to the geomagnetic and solar sources. In general, TEC tends to demonstrate strong transiency below 30 days and these sources contributing to potentially large amplitude changes have to be removed from the raw TEC data prior to PETA statistical analyses (Afraimovich and Astafyeva 2008; Kutiev et al. 2013). For instance, Kutiev et al. (2005) studied TEC behavior during geomagnetic storms by sequentially removing diurnal, seasonal and solar sources, where the residual TEC signal was subsequently presumed to be geomagnetic in nature. The strong 27-day (i.e. medium-term) solar periodicity observed in their study was accounted for through

Fourier wave approximations. Geomagnetic variations were also shown to possess significant oscillations at shorter periods of 9 and 13.5 days (Kutiev et al. 2012).

The ensuing statistical envelope method (i.e. Eq. 2) holds a two-fold purpose. Firstly, through an appropriate length of window N , diurnal and seasonal variations are captured in the statistical mean. An incorrect selection of N leads to leakage of periodicities away from the TEC thresholds (Kutiev et al. 2005). The TEC thresholds should ideally contain the background periodicities, thus N has to be small in order to capture transient ionospheric states. However, a reasonable lower bound of N was not prescribed by Kutiev et al. (2005). Frequencies corresponding to short- (i.e. semi-diurnal and diurnal) and medium-term (i.e. space weather) periodicities can be removed using a combination of wavelet transform and the statistical method. The window size N was selected equal or less than the space weather periodicities identified from a fast-Fourier transform. Consequently, a TEC signal free of space weather influences (i.e., TEC_{β}) is obtained. Using a 95% confidence interval corresponding to a z-value of 1.96 (i.e., approximately 2s) was used to test TEC_{β} for potential anomalous TEC behavior. If a TEC_{β} value exceeds the confidence thresholds, the anomaly could not be due to space weather influences and the assumed null hypothesis (i.e. anomaly is not due to the earthquake) is rejected (Flechner and Tseng 2011). In summary, a TEC signal free of space weather periodicities (i.e., TEC_{β}) is first obtained through the inverse wavelet transform by reconstructing the signal using wavelet coefficients (Montejo and Suarez 2013; Torrence and Compo 1998). Subsequently, Eq. 2 is applied for the detection of PETA using TEC_{β} signal instead of the raw TEC signal, where a suitable N value was employed to account for remaining periodicities (e.g. diurnal). A summary of the proposed method used to identify PETA is illustrated in Figure 2.

3 Statistical Results

The objective of the wavelet transform analysis is to identify the solar and geomagnetic influences on the raw TEC signal. Annual wavelet spectrum plots at several locations (i.e. listed in Table 2) are presented in Figure 3. Note that when performing the conversion to period in days, the frequencies were scaled by a factor of 1/24. From Figure 2, it is apparent that solar influence dominates the raw TEC signal approximately between the scaled frequencies of 8 to 16 μHz , which is equivalent to a period of 17.4 to 34.7 days. This range is demarcated on the plots as solid red lines and is consistently present throughout the different locations. Additionally, the peak amplitudes due to these solar effects (i.e. red-dashed regions in Figure 3) can be narrowed down to within 22.1 and 27.2 days (highest value at 25.4 days). While solar-induced TEC changes are exhibited throughout the year, amplifications of wavelet amplitudes at various periods demonstrate a clear seasonal effect since solar rotation control is considerably affected by seasonal variations. Solar effects appear to be most significant approximately between mid-March and end-May as well as between mid-September to end-November. There are also distinct differences between the peak wavelet amplitudes across locations (likely due to the equatorial ionization anomaly (EIA)). It is known that ionospheric conditions at equatorial and low-latitude regions are temporally and spatially dynamic (Aggarwal 2011; Kumar and Singh 2009). As shown in Figure 3, Indonesia possessed large TEC wavelet amplitude changes (i.e. up to 35 times that of non-affected frequencies) as compared to places such as New Zealand, where solar effects were comparatively weaker. Based on these observations, past methods of setting standardized thresholds (i.e. one-size-fits-all approach) for indices such as F10.7 without appropriate consideration for geographic regions would result in erroneous interpretations of space weather activity. For instance, a threshold based on Indonesia may be unrealistically high for

New Zealand and could yield false negative results (Type II errors) in such areas (the converse is also true).

Geomagnetic influences, although more than twice weaker in magnitude than solar sources, are also clearly distinguishable in the wavelet spectrum (i.e. regions defined by yellow lines). These signals exhibit periodicities between 8 to 17 days (mean at 12.5 days), corresponding to scaled frequencies of approximately, 16 to 32 μHz . Since geomagnetic disturbances are the consequence of relative velocities at the interface region between low- and high-speed solar plasma, it generally reflects seasonal variations similar to solar rotation control (Kutiev et al. 2012). Consequently, the removal of solar and geomagnetic effects involves rejecting scaled frequencies between 8 to 32 μHz such that the reconstructed signal does not contain space weather influences. Additionally, presence of high frequencies (i.e. beyond the 32 μHz range), which are more pronounced in places such as Japan and Mexico, were excluded to eliminate spurious signal peaks due to diurnal variations. It ought to be noted that if a TEC anomaly of seismic origin does indeed exist, it is presumed to manifest at frequencies outside this range. Such an assumption is reasonable because in the case where the seismic-induced TEC fall within this range (especially within 8 to 32 μHz), it would be dwarfed by the solar rotation fluctuations and is unlikely to be detected by a single statistical test.

Once the filters have been applied, the reconstructed TEC_β signals over locations listed in Table 2 were used for statistical envelope analysis. To select an appropriate window length N , TEC spectral densities were utilised to localise periodicities for the space weather signals. Figure 4 shows the corresponding spectral density plots for the same locations shown in Figure 3. The observed geomagnetic periodicities (i.e. within the grey regions) show that its periods vary between approximately 8.3 and 12.5 days. For the cases of Japan, Peru and Mexico, geomagnetic periods were more significant at 8.3 days as compared to Indonesia. As for locations of Nepal and New Zealand, geomagnetic effects though vaguely present, were clearly much weaker than the solar-induced variations. As geomagnetic (and solar) contributions are inherently a global phenomenon, the value of N was thus selected based on the shortest periodicity observed at 8.3 days to account for short-term fluctuations. Figure 5 illustrates the results from the variations of TEC_β at various locations listed in Figure 3 while the statistical assessments of TEC anomalies for the earthquake database in Table 2 are presented in Table 3. Here, anomaly directionality refers to the exceedance of TEC_β beyond the upper (i.e. positive) or lower (i.e. negative) bounds, while its amplitude indicates the percentage difference between the observed TEC_β and its respective bound on the anomalous epoch. In general, the appearances of abnormal TEC_β levels were discovered days prior to each large seismic event. As shown in Figure 6, multiple TEC_β anomalies can continue to show up at different number of days prior to the earthquakes. The range of precursory days varies between 1 to 10 days with most earthquakes displaying anomalous TEC_β signals occurring at 4 days before the earthquake onwards. The earliest TEC_β anomalies were observed at approximately 2 weeks (i.e. within short-term periods) before the earthquake with 30% of the cases exhibiting initial TEC_β anomalies at 12 and 4 days before the earthquake. Overall, the initial TEC_β anomalies were observed around 7.9 days before the earthquake and have a standard deviation of 3.5 days. Various authors have identified possible links between precursor manifestation times and fundamental seismic characteristics such as magnitude and focus (Astafyeva and Heki 2011; Le et al. 2011; Yiyan et al. 2009). Figure 7 further explores the relations between the PETA manifestations and the underlying fault

mechanisms of each earthquake. Figure 7a illustrates the initial appearance of PETA with the three major fault mechanisms – reverse (i.e. compressional), thrust (i.e. extensional) and strike-slip (i.e. translational) and Figure 7b shows the number of PETA anomalies occurring in relation to these fault types. Initial PETA appears, on average, about 7 to 8 days before the earthquake and about two days with anomalous TEC_β will be detected, irrespective of fault mechanism. Additionally, while both positive and negative TEC_β anomalies were present, there was no clear preference for either. The directionality of these TEC_β anomalies could likely to be influenced by the direction of anomalous electric field at ground surface and position of ionospheric regions (Choi et al. 2012; Pulinets et al. 2003). The anomaly amplitudes vary widely, with most cases exhibiting anomalies up to 20% from the usual variations (Figure 8). Moreover, there were several events which possessed significant anomalous variations larger than 100% (especially the 2015 Tajikistan M7.2 earthquake (ID. 24)). Previously, Astafyeva et al. (2014) discovered that small displacement earthquakes of the strike-slip mechanism, similar to the Tajikistan event, are able to generate large ionospheric perturbations comparable to dip-slip earthquakes. In addition, the amplitudes of these ionospheric perturbations can be further emphasized in the detection methodology if data processing and filtering methods (i.e. wavelet-based band filters in this case) are employed. Finally, geographic variations did not appear to influence the TEC anomalies.

4 Revisiting Negative Case Studies

4.1 Rhoades et al. (2015)

Rhoades et al. (2015) examined TEC variations over New Zealand for four earthquakes. They concluded that while a short-term TEC anomaly was observed for only one of them (i.e. 2011 M6.3 Christchurch earthquake), it is likely to be a result of a solar flare-induced geomagnetic anomaly. Rhoades et al. (2015) adopted a two-fold approach, where they conducted a statistical envelope test followed by the precursor mask technique, which is essentially a correlation test (Lomonosov et al. 2000; Pulinets et al. 2002). It is noted that even though Rhoades et al. (2015) alluded to the concept of earthquake preparation zone (EPZ), they do not select the external ground station (i.e. presumably free from seismic influence) based on the conventional EPZ formulation proposed by Dobrovolsky et al. (1979) (Pulinets 2004). For instance, the M6.3 Christchurch earthquake will necessitate an EPZ radius of approximately 511 km. However, a threshold distance of 250 km was employed. Hence, it is expected that the ionospheric conditions of the internal (i.e. within the EPZ) and external (i.e. outside the EPZ) ground stations are similar. Thus, the degree of correlation between TEC of the two stations is understandably high, mostly implying the absence of anomalous TEC signals.

Using the proposed approach, the Christchurch event, where a solar flare originating on 15 February 2011 was the source of contention for the observed TEC anomaly three days later, was re-examined. Here, the existence of the solar flare was confirmed based on x-ray flux observations from the GOES-15 platform. The wavelet spectrums for both short and long channels (corresponding to 0.05 to 0.4 nm and 1 to 8 nm, respectively) are illustrated in Figure 9. It can be seen that the solar flare occurrence affecting the dates between 15 and 18 February 2011, fall within the scaled frequencies (i.e. 8 to 32 μ Hz) identified to be space weather periodicities. After filtering out these frequencies, the TEC_β variation for the Christchurch event is presented in Figure 10a (for the same range of analysis dates) which shows anomalous TEC_β behavior around 11 and 7 days prior to the earthquake (i.e. 10 and 14 February 2011, respectively). This was not within the supposed period affected by space weather activity mentioned by Rhoades et al. (2015). This significant enhancement on 14

February 2011 was close to 110% from the normal variation (i.e. upper limit), while the slightly weaker anomaly was around 68.7%. Using the proposed approach, anomalous TEC_{β} was also detected for the remaining three earthquakes reported in Rhoades et al. (2015) as illustrated in Figures 10b to 10d and summarized in Table 4. It is worth noting that where Rhoades et al. (2015) employed a detection confidence of approximately 82%, the anomalies detected here were at least 95% confidence.

4.2 Thomas et al. (2017)

Thomas et al. (2017) examined the claims of Le et al. (2011) on the observed PETA from a large number of global earthquakes and concluded that the apparent anomalies were not statistically significant. In particular, Thomas et al. (2017) raised the examples of two large magnitude earthquake cases (i.e. 2010 Chile M8.8 and 2011 Japan M9.0) where geomagnetic activity (indicated by the Dst index) could explain the anomalous TEC readings. Following Le et al. (2011), they excluded days which were geomagnetically ‘disturbed’ identified by two criteria (see Table 1). While it was not clearly stated by Thomas et al. (2017), the supposedly geomagnetically disturbed periods for the 2011 Japan event were presumed to be 14 to 16 February, 1 to 3 as well as 10 to 11 March 2011 (i.e. day of earthquake). As for the 2010 Chile event, the disturbed period was approximately from 15 to 18 February 2010.

The two earthquake events are re-examined using the proposed approach. To inspect the correlations between the two parameters (i.e. Dst and TEC) near the earthquake times, a wavelet coherence test was conducted using the aforementioned earthquake cases. Figure 11 presents the wavelet coherence spectrum between TEC and Dst index for the two earthquake events. As highlighted by Thomas et al. (2017), strong correlations were indeed observed near both earthquake times, thereby implying a significant geomagnetic stimulus on the ionospheric TEC. Furthermore, the effect of geomagnetic activity on TEC was prominent for an extended period of approximately two weeks (i.e. 13 and 17 days for the 2010 Chile M8.8 and 2011 Japan M9.0, respectively). This suggests that discounting single days at the exceedance of a prescribed threshold is not an effective way (i.e. insufficient) to account for these influences. Filtering in the proposed approach can eliminate these effects, since the correlations were greatest at the identified geomagnetic scaled frequencies (i.e. approximately 16 to 32 μHz shown in Figure 11). For the entire month of February 2010 (Chile event), Figure 12 illustrates a TEC_{β} depletion (approximately 66.8% decrease from the normal fluctuations) on the day of the earthquake as well as a significant TEC_{β} enhancement (about 17 days earlier) which was more than twice the normal fluctuations ($> 200\%$). Furthermore, it can be observed that these two anomalous days do not reside within the geomagnetically disturbed period previously flagged by Thomas et al. (2017) (note: the 2011 Japan event is shown earlier in Figure 5).

4.3 Guo et al. (2016)

Guo et al. (2016) investigated the presence of TEC anomalies over the region of south-western China where there is frequent seismic activity. For a database of 18 earthquakes occurring between 2001 and 2013 with magnitudes between M_w 6.0 to 8.0, they found that 72.2% (i.e. 13 cases) of the earthquakes exhibited TEC anomalies mostly within 15 days prior to each seismic event. The authors particularly highlighted the M_w 6.1 event which happened on 11 August 2013 in Tibet, where a TEC anomaly manifested 19 days earlier.

Using the proposed approach, an analysis was conducted on the M_w 6.1 event. Figure 13 illustrates the results in the TEC_{β} time series with range of dates similar to Guo et al. (2016),

where anomalies were represented by ΔTEC_{β} (i.e. percentage exceedance of TEC_{β} from its normal variation). The main features of the TEC anomaly presented by Guo et al. (2016) were observed here – 1) large positive ΔTEC_{β} ($\sim 74.8\%$) on 23 July 2013 (i.e. 19 days before earthquake), and 2) minor positive ΔTEC_{β} ($\sim 47.7\%$) on 10 July 2013 (i.e. 1 day before earthquake). Due to a geomagnetic storm, Guo et al. (2016) excluded anomalies which were within 1 to 3 days after 5 August 2013. Without excluding anomalies in this fashion in Figure 13, the proposed wavelet-based approach yielded no anomalies within this period (i.e. 5 to 8 August 2013, although both Dst and Kp indices showed mostly normal geomagnetic behavior on the 8th). This was due to rejection of geomagnetic frequencies when the frequency filters were applied to obtain TEC_{β} . Finally, the earthquake cases (i.e. ID. 1, 6, 10, 12, 13) which were identified by Guo et al. (2016) as having no anomalies were re-examined using the proposed approach and were found to all exhibit TEC_{β} anomalies up to 13 days before the earthquake. The findings are summarized in Table 5.

5 Conclusion

While there is vast literature highlighting the enhancement or depletion in ionospheric total electron content (TEC) prior to earthquakes, many of the existing methodologies become problematic when space weather effects are present. In this study, various definitions of ‘normal’ space weather indices were firstly examined to emphasize the disparities between these thresholds. The continuous wavelet transform method was utilized to localize frequencies corresponding to solar and geomagnetic periodicities where contributions from these solar-induced origins could be removed by filtering and to construct a TEC_{β} signal free from background noise (TEC_{β}). Secondly, the window length N, which is vital for anomaly detection in the statistical envelope method was examined. In order to account for short-term fluctuations and to transfer periodicities to statistical means, an N value corresponding to the shortest geomagnetic period of 8.3 days was utilized to construct the envelope in order to identify anomalous TEC_{β} . Using the proposed approach, a database of 30 large seismic events was analysed to show that TEC_{β} anomalies (whether positive or negative enhancements) were detected for all the earthquakes and multiple occurrences of PETA could be detected days prior to the earthquakes. Majority of the cases registered anomalies at approximately 4 days before the seismic event, although the ranges of precursory days vary between 1 and 10 days. Overall, the initial TEC anomalies were mostly found at 12 and 4 days before the earthquake. An examination of precursory days in relation to seismic fault mechanisms revealed that the initial PETA will be detected, on average, 7 to 8 days before the earthquake with 2 days possessing anomalous TEC activity, irrespective of fault mechanism. Further research is needed to quantify the nature of these observations in relation to seismic characteristics. For majority of the cases, anomalous TEC_{β} was found to be within 20% of its normal variation, defined by a 95% confidence interval. The TEC_{β} of several seismic events also showed large degree of anomalous TEC_{β} behavior (greater than 100% of its normal variation), likely related to their fault mechanisms. In addition, re-visiting several previous negative case studies showed that TEC_{β} anomalies could be detected in all the negative cases using the proposed approach.

In the current study, ionospheric TEC and PETA for the various seismic events were examined at the epicenters’ location, with the assumption that any TEC enhancement or depletion are likely to be greatest within its vicinity. However, there have been several case studies demonstrating that such an assumption may not be true (i.e. greatest TEC anomaly

occurs at some distance away from the epicenter) even though a TEC anomaly is still registered at the epicenter itself. Thus, more research is required to ascertain if there is a systematic link between an earthquake's epicenter (or hypocenter) and manifestation of the TEC anomaly in order to employ this precursor for earthquake forewarning. Besides space weather effects, other geophysical processes such as volcanic eruptions (e.g. Lin 2013), tsunami (e.g. Galvan et al. 2012) as well as anthropogenic events such as nuclear explosions (e.g. Kakinami et al. 2011) and rocket launches (Ding et al. 2014; Kakinami et al. 2013) have been shown to trigger agitations to the ionosphere. However, the simultaneous occurrences of these processes with earthquakes are rare compared to space weather phenomena. Nonetheless, the possibility for such non-earthquake related TEC anomalies have to be accounted for in using the proposed approach for earthquake forewarning.

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Table 1 Threshold levels of space weather indices for low/quiescent conditions

Index (units)	Nature	Value	Reference(s)	
F10.7 (solar flux units)	Solar	70	Guo et al. (2015)	
		100	Akhoondzadeh (2013b)	
			Guo et al. (2016)	
			Mayaud (1980)	
		120	Parrot (1995)	
			Hayakawa and Molchanov (2002)	
Liu et al. (2004)				
		Pulinets and Boyarchuk (2004)		
		130	Akhoondzadeh (2013a)	
		-10	Klimenko et al. (2011)	
Dst (nanoTesla)	Geomagnetic	-15	Hasbi et al. (2011)	
			Mayaud (1980)	
			Parrot (1995)	
			Hayakawa and Molchanov (2002)	
		-20	Liu et al. (2004)	
			Pulinets and Boyarchuk (2004)	
			Akhoondzadeh and Saradjian (2011)	
			Dogan et al. (2011)	
			-30	Guo et al. (2016)
			-40 ¹	Thomas et al. (2017)
				Choi et al. (2012)
				-50
Oikonomou et al. (2016)				
		-60	Kon et al. (2011)	
		2	Klimenko et al. (2011)	
			Mayaud (1980)	
	Parrot (1995)			
	2.5		Hayakawa and Molchanov (2002)	
		Liu et al. (2004)		
Pulinets and Boyarchuk (2004)				
Kp	Geomagnetic		Akhoondzadeh and Saradjian (2011)	
			Rostoker (1972)	
			Chauhan et al. (2009)	
		3	Singh et al. (2009)	
			Guo et al. (2016)	
			Ulukavak and Yalcinkaya (2016)	
		4	Hasbi et al. (2011)	
			Fuying and Yun (2011)	
		5	Dogan et al. (2011)	
			Lin (2011)	
		6	Karatay et al. (2010)	
		20 ²	Karia et al. (2012)	
30 ³	Ke et al. (2016)			

¹ Also for decrease within a day

² Cumulative value over a span of 8 days

³ Daily cumulative value

Table 2 Catalog of large ($M \geq 7.0$) earthquakes

ID.	Date	Latitude ($^{\circ}$) ¹	Longitude($^{\circ}$) ²	Focal depth (km)	Magnitude (M_w)
1 ³	11/03/2011	38.3	142.4	29	9.0
2	24/06/2011	52.1	-171.8	52	7.3
3	24/08/2011	-7.6	-74.5	147	7.0
4	23/10/2011	38.7	43.5	18	7.1
5	20/08/2011	-18.4	168.1	32	7.2
6	25/03/2012	-35.2	-72.2	41	7.1
7	07/12/2012	37.9	143.9	31	7.3
8	20/03/2012	16.5	-98.2	20	7.4
9 ³	11/04/2012	2.3	93.1	20	8.6
10	02/02/2012	-17.8	167.1	23	7.1
11	06/04/2013	-3.5	138.5.	66	7.0
12	16/04/2013	28.0	62.0	80	7.7
13	24/09/2013	27.0	65.5	15	7.7
14 ³	25/09/2013	-15.8	-74.5	40	7.1
15	15/10/2013	9.9	124.1	19	7.1
16	23/06/2014	51.8	178.7	109	7.9
17	01/04/2014	-19.6	-70.8	25	8.2
18	14/10/2014	12.5	-88.1	40	7.3
19	15/11/2014	1.9	126.5	45	7.1
20 ³	18/04/2014	17.4	-101.0	24	7.2
21	26/10/2015	36.5	70.4	213	7.5
22	05/05/2015	-5.5	151.9	55	7.5
23	24/11/2015	-10.5	-70.9	606	7.6
24	07/12/2015	38.3	72.8	26	7.2
25	25/12/2015	-43.4	-73.9	38	7.6
26 ³	25/04/2015	28.1	84.7	15	7.8
27	16/04/2016	0.4	-79.9	21	7.8
28	02/03/2016	-4.9	94.3	24	7.8
29	16/04/2016	32.8	130.7	10	7.0
30 ³	14/11/2016	-42.8	173.1	15	7.8

1 Negative values refer to south

2 Negative values refer to west

3 These locations are referenced in Figure 3.

Table 3 Assessment of TEC_{β} anomalies for earthquake catalog

ID.	No. of days before earthquake ¹	Directionality ²	Anomaly amplitude (%) ³	Fault mechanism
1	9, 8, 7	+, +, +	102.9, 3.9, 40.7	reverse
2	8, 4	+, +	4.3, 18.6	normal
3	5, 4	-, -	20.1, 3.2	normal
4	8, 2	+, +	57.3, 5.4	reverse
5	2	-	7.0	reverse
6	13, 10, 6	+, +, -	68.3, 6.8, 3.4	reverse
7	10	+	24.3	reverse
8	11, 2	-, -	101.2, 8.24	reverse
9	6, 4	-, -	169.6, 13.8	strikeslip
10	6	+	6.5	normal
11	12, 5, 3	-, +, +	7.6, 100.3, 12.2	normal
12	12, 8, 2	+, +, -	162.6, 6.5, 61.5	normal
13	5, 3	+, +	159.3, 48.7	strikeslip
14	8, 1	+, +	16.1, 147.5	reverse
15	12, 9, 6	+, -, +	602.7, 5.8, 103.9	reverse
16	11, 10, 4	+, +, -	37.4, 34.4, 71.1	normal
17	4	+	32.6	reverse
18	2, 1	-, -	13.1, 17.0	normal
19	4	-	285.4	reverse
20	5	-	239.8	reverse
21	11, 10, 9, 8	+, +, +, +	18.5, 644.8, 72.8, 35.8	reverse
22	12, 10	+, -	11.7, 183.2	reverse
23	4, 3	-, -	219.1, 136.1	normal
24	12, 7	-, +	31.7, 908.8	strikeslip
25	4	+	539.7	reverse
26	3, 2	+, +, +	2.4, 16.2	reverse
27	10, 3, 2	-, +, +	12.9, 117.0, 8.5	reverse
28	6	-	104.4	strikeslip
29	12, 3, 1	+, +, -	18.6, 85.0, 6.4	strikeslip
30	4	+	50.6	reverse

¹ Occurrences of TEC_{β} anomalies² Positive and negative anomalies refer to the exceedance of TEC_{β} from the upper and lower bounds, respectively³ Percentage difference between anomaly and detection bound

Table 4 Assessment of TEC_{β} anomalies for New Zealand earthquakes in Rhoades et al. (2015)

ID	No. of days before earthquake ¹	Directionality	Anomaly amplitude (%) ²
Darfield	6	-	17.5
Christchurch	11, 7	+, +	68.7, 109.9
Seddon	16, 11	+	30.3, 20.3
Lake Grassmere	12, 2, 1	+, +, +	23.6, 81.0, 9.1

¹ Occurrences of TEC_{β} anomalies

² Percentage difference between anomaly and detection bound

Table 5 Other earthquake cases¹ studied by Guo et al. (2016)

ID.	No. of days before earthquake ²	Directionality	Anomaly amplitude (%) ³
1	13	+	47.7
6	12, 11, 10	+, +, +	22.1, 64.5, 36.0
10	8, 2	-, -	6.6, 17.1
12	12, 11, 7, 1	-, -, -, +	15.9, 13.7, 12.4, 555.1
13	7, 6	-, -	199.3, 85.4

¹ These cases were found to possess no anomalies previously

² Occurrences of TEC_{β} anomalies

³ Percentage difference between anomaly and detection bound

Figure 1 Distributions of seismic precursors studied in the literature (up to 2015)

Figure 2 PETA-detection methodology employed in the current study

Figure 3 Typical raw ionospheric TEC wavelet spectra at various earthquake locations; (dashed) red and yellow lines denote range of frequencies under (strong) solar and geomagnetic influence respectively; white dashed lines denote cone of influence (COI)

Figure 4 Spectral density plots (for same locations shown in Figure 3) showing differences in dominant geomagnetic periodicities and overall amplitudes; grey regions show periodicities under geomagnetic influence

Figure 5 TEC_{β} time series (for locations shown in Figure 3); shaded bar indicates PETA

Figure 6 Occurrences of TEC_{β} anomaly prior to earthquake events

Figure 7 Relationships between a) number of days before earthquake (initial PETA) and b) number of PETA occurrences, with seismic fault mechanisms

Figure 8 Number of cases at each anomaly amplitude range

Figure 9 Wavelet spectrum of solar x-ray flux for February 2011 (left – short channel; right – long channel); red box indicates solar flare associated with M6.3 Christchurch event; black-dashed lines indicate frequencies corresponding to space weather effects

Figure 10 TEC_β time series for a) 2011 M6.3 Christchurch, b) 2010 M7.1 Darfield, c) 2013 M6.5 Seddon, and d) 2013 M6.6 Lake Grassmere earthquakes; shaded bar indicates PETA

Figure 11 Wavelet coherence between TEC and Dst index for 2010 Chile M8.8 (left) and 2011 Japan M9.0 (right); red regions indicate high coherence (greater than 0.9); black arrow denotes earthquake day

Figure 12 TEC_β time series (for 2010 M8.8 Chile earthquake); shaded bar indicates PETA

Figure 13 TEC_{β} time series (for 2013 M6.1 Tibet); shaded bar indicates PETA